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A PROGRAM TO DETERMINE THE POINTING ANGLE TO A SPECULAR POINT

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This report describes a method for determining the pointing angle to a specular point given attitude information to the IBSS SPAS.

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A program to determine the pointing angle to a specular point.

This report describes a method for determining the pointing angle to a specular point given the latitude, longitude, inclination, yaw and pitch of the IBSS SPAS. The formulas for the parameters of the sun are taken from *Astronomical Formulae for Calculators.*[1]

The following variables that refer to the SPAS are obtained from SPAS ephemeris data furnished by Mission Research Corporation.

O_X	= X component of the position vector (km) ECI
O_X	= Y component of the position vector (km) ECI
O_Z	= Z component of the position vector (km) ECI
GEOCLAT	= geocentric latitude (+90°)
SPASLON	= geocentric longitude (+E)
V_X	= X component of velocity vector (km/sec)
V_Y	= Y component of velocity vector (km/sec)
V_Z	= Z component of velocity vector (km/sec)
H_{SPAS}	= distance (km) to the SPAS from the center of the earth.

The calendar year, month and day associated with each of these quantities are also obtained from the SPAS ephemeris data.

YAW and PITCH are obtained from the SPAS attitude data furnished by Mission Research Corporation.

The SPAS longitude, as given in the ephemeris, is measured positive toward the east. The formulae in this analysis assume that the SPAS longitude is positive toward the west. Therefore, SPASLON is made equal to -SPASLON.

The components of the SPAS inclination vector, given the position and velocity vectors can be written as:

$$I_x = O_y * V_z - O_z * V_y$$

$$I_y = O_z * V_x - O_x * V_z$$

$$I_z = O_x * V_y - O_y * V_x.$$

The inclination angle, INCL, of the SPAS is then

$$INCL = \cos^{-1}\left[\frac{I_z}{[I_x^2 + I_y^2 + I_z^2]^{1/2}}\right].$$

[1] J. Meeus, *Astronomical Formulae for Calculators*, Willmann-Bell, Richmond, VA (1988).

The SPAS heading angle measured from true north, HEAD, is computed from:

$$HEAD = \tan^{-1}\left[\frac{\cos(INCL)}{[\sin^2(INCL) - \sin^2(GEOCLAT)]^{1/2}}\right].$$

If the SPAS is traveling from north to south, determined by examining the latitudes, the supplement of the heading angle is used. The azimuth from true north and elevation measured from the local horizon of the SPAS line-of-sight are determined as follows:

AZIMUTH = YAW + HEAD

ELEVATION = PITCH.

The Julian date, JD, is computed from:

JD = INT (365.25 y) + INT (30.6001 (m+1)) + DD.dd + 1720994.5+ B

where INT is the integer part of the value in parentheses and DD.dd is the decimal day, y is the year and m is the month at the time of the calculation.

$$B = 2 - A + \left|\frac{A}{4}\right|, \text{and}$$

$$A = \left|\frac{y}{100}\right|,$$

The time T, measured in Julian Centuries of 36525 ephemeris days from the epoch 1900 January 0.5 ET, is given by

$$T = \frac{JD - 2415020.0}{36525}.$$

Since T is expressed in centuries, an error in the 5th decimal place will cause an error of 0.4 days in the time. Therefore, it is essential that this calculation be done in double precision.

The geometric mean longitude of the sun, L, referred to as the mean equinox of the date, is given by:

$$L = 279.69668 + 36000.76892\,T + 0.0003025\,T^2.$$

The mean anomaly of the sun, M, is expressed as:

$$M = 358.47583 + 35999.04975\,T - 0.000150\,T^2 - 0.0000033\,T^3.$$

The equation for the center of the sun, C, is determined from:

$$C = (1.919460 - 0.004789\,T - 0.000014\,T^2)\sin(M) + (0.0200943 - 0.000100\,T)\sin(2M) + 0.000293\sin(3M).$$

The true longitude of the sun, θ, equals

$$\theta = L + C.$$

This longtitude must be modified to obtain the apparent longitude of the sun, referred to as the true equinox of the date. θ is corrected for mutation and aberration as follows:

$$\Omega = 259.18 - 1934.142\,T$$

$$\theta_{APP} = \theta - 0.000569 - 0.00479\sin(\Omega).$$

The obliquity of the ecliptic, ε, is given by

$$\varepsilon = 23.452294 - 0.0130125\,T - 0.00000164\,T^2 + (9.2100 + 0.00091\,T)\cos(\Omega)/3600.0.$$

The right ascension at the sun, γ, is given by the formula

$$\gamma = \frac{180}{15\pi}\tan^{-1}\left(\frac{\cos\varepsilon\,\sin(\theta_{APP})}{\cos(\theta_{APP})}\right)\ (hours).$$

The declination of the sun, δ, is given by

$$\sin(\delta) = \sin(\theta_{APP})\sin(\varepsilon).$$

The coordinates of the sun relative to the position of the satellite must be determined.

The sidereal time at Greenwich at 0 hr. UT expressed in decimal hours in the interval 0-24 hours is given by the formula:

$$TIME_S = 0.276919398 + 100.0021359\,T.$$

The sidereal time at Greenwich at the time of the calculation, T_{S_CAL}, is therefore:

$$T_{S\_CAL} = 1.00273908 * TIME_{CAL} + TIME_S$$

where $TIME_{CAL}$ is in decimal hours.

The local hour angle in degrees is

$$LHA = T_{S\_CAL} - SPASLON - \gamma.$$

The angle A in Fig. 1, which is the compliment of the solar zenith angle, is given by:

$$A = \sin^{-1} [\sin (GEOCLAT) \sin (\delta) + \cos (GEOCLAT) \cos (\delta) \cos (LHA)].$$

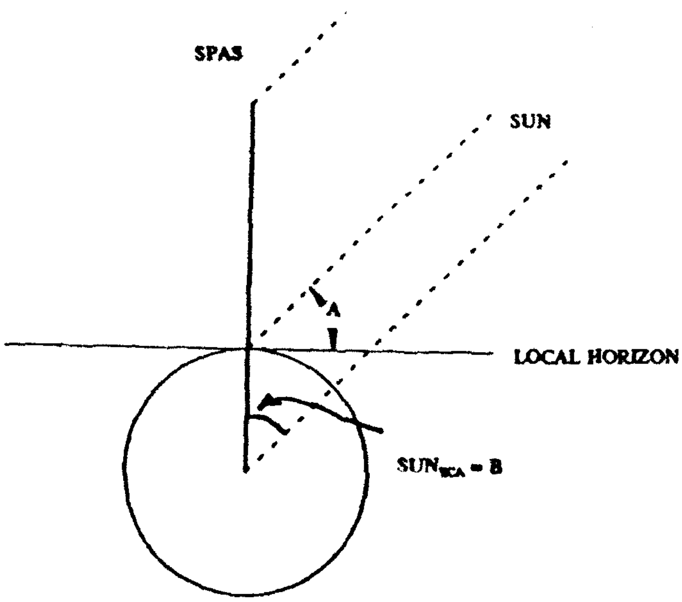

Figure 1. SUN-SPAS-EARTH Geometry.

The earth center angle between the SPAS and the sun, the solar zenith angle of the SPAS, is

$$SUN_{ECA} = 90° - A.$$

The azimuth to the specular point, i.e., azimuth of sun, is defined as:

$$AZ_{SPEC} = \tan^{-1} \left[\frac{\sin (LHA)}{\cos (LHA) \sin (GEOCLAT) - \tan (\delta) \cos (GEOCLAT)} \right] + 180°.$$

Five specular point altitudes are assumed, specifically 40, 30, 20, 10 and 0 km. An iterative procedure is necessary to calculate the earth center angle between the SPAS and the specular point.

With B equal to SUN_{ECA}, $H_{SPECULAR}$ equal to one of the 5 specular point altitudes measured from the center of the earth, and B′ initially equal to B the following parameters are computed:

$$X_1 = 2B' - B$$

$$FN = \frac{H_{specular}}{H_{spas}} \sin(B') - \sin(X_1)$$

$$FN' = \frac{H_{specular}}{H_{spas}} \cos(B') - 2\cos(X_1) .$$

A new value for B′ is then determined from:

$$B'_{n+1} = \left| B'_n - \frac{FN}{FN'} \right| .$$

A check is made to see if (B-B′) is less than 0.0001. If it is not X_1, FN and FN′ are recomputed using the new B′. This process is repeated until (B_{n+1} - B'_n) becomes less than 0.0001. The earth center angle between the satellite and the specular point is then given by:

$ECA_{SAT-SPEC}$ = B - B′.

The formalae used in this iteration can result in a B′ that is greater than 360°. Therefore, B′ must be reduced by multiples of 360° until an angle less than 360° is reached.

Figure 2 illustrates the geometry described above.

The elevation to the specular point is given by:

$ELEV_{SPEC}$ = -[90° + SUN_{ECA} - 2 B′].

If B′ is greater than 90°, there is no specular point for the given input parameters.

The distance D in kilometers from the SPAS to the specular point is given by:

$$D^2 = H_{SPAS}^2 + H_{SPECULAR}^2 - 2H_{SPAS} H_{SPECULAR} \cos(ECA_{SAT-SPEC}) .$$

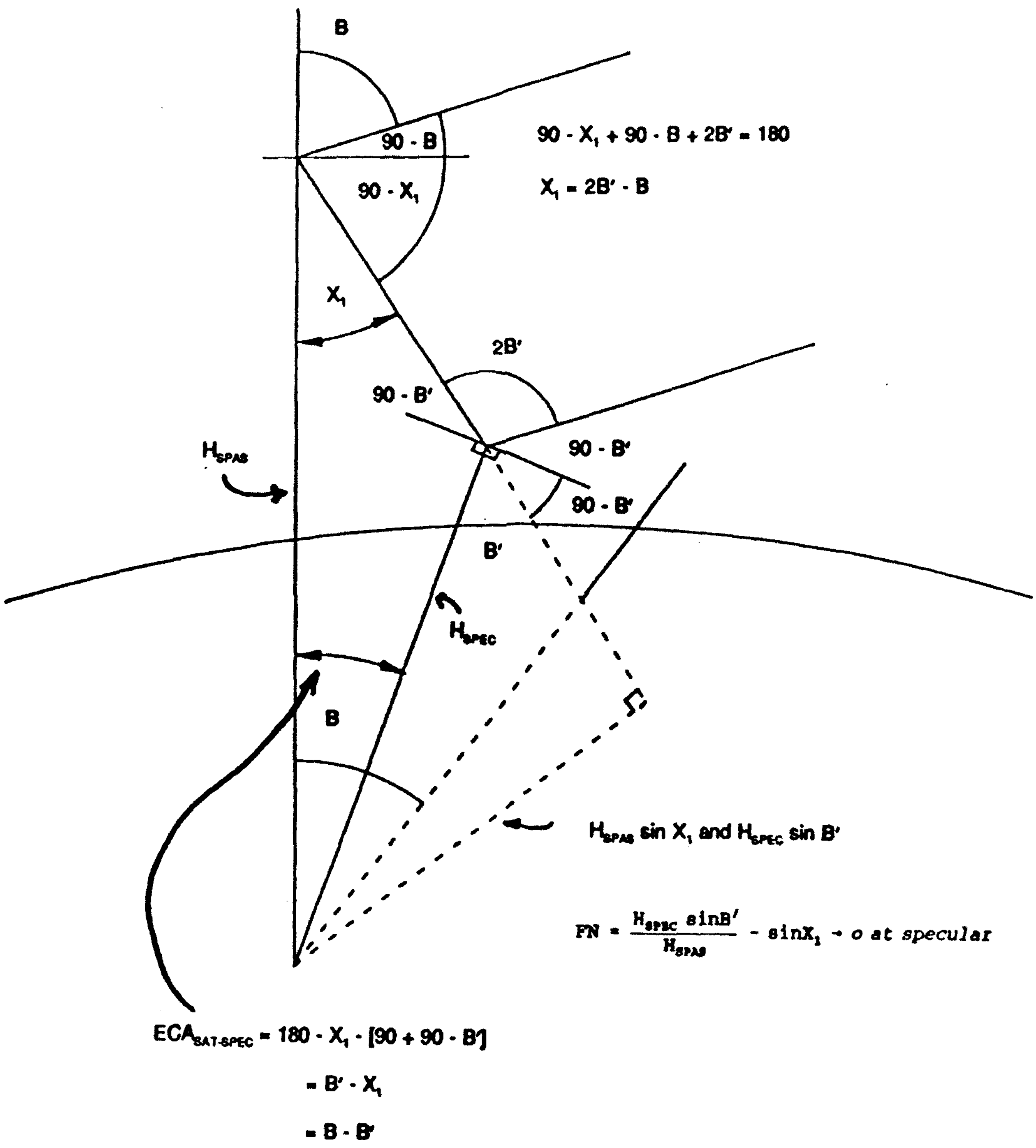

Figure 2. Specular Scattering Geometry

The latitude, LAT_{SPEC}, of the specular point is defined as:

$$LAT_{SPEC} = \sin^{-1}[\cos(ECA_{SAT-SPEC})\sin(GEOCLAT) + \sin(ECA_{SAT-SPEC})\cos(GEOCLAT)\cos(AZ_{SPEC})] .$$

The longitude of the specular point is determined in the following manner. First the parameters A_1 and A_2 are computed from:

$$A_1 = \sin^{-1}\left[\frac{\sin(ECA_{SAT-SPEC})\sin(AZ_{SPEC})}{\cos(LAT_{SPEC})}\right]$$

$$A_2 = \frac{\cos(ECA_{SAT-SPEC}) - \sin(GEOCLAT)\sin(LAT_{SPEC})}{\cos(GEOCLAT)\cos(LAT_{SPEC})} .$$

A_2 is the cos of A_1, however only the sign of A_2 is required to determine λ, the longitudinal difference $LONG_{SPAS}$ - $long_{SPEC}$.

If $A_1 \geq 0°$ and $A_2 < 0$, then $\lambda = \pi - A_1$

If $A_1 < 0°$ and $A_2 < 0$, then $\lambda = -\pi - A_1$.

If $A_2 > 0$, then $\lambda = A_1$.

The longitude of the specular point is then

$LONG_{SPEC} = SPASLON - \lambda$.

Since $LONG_{SPEC}$ must be between 0 and 360°, the same modification must be made to it as was done for B′ to insure that it stays within this range.

The pointing angle to the specular point is defined as:

$$P = \cos^{-1}[\cos(ELEV_{SPEC})\cos(ELEVATION)\cos(AZIMUTH-AZ_{SPEC}) + \sin(ELEV_{SPEC})\sin(ELEVATION)]$$

The results of a typical calculation are shown in Table 1. The first column contains the day of the year (0 - 365), the hours of the day, the minutes of the hour and the seconds of the minute. The time is given in GMT. The next column contains the mission elapsed time (sec). The third column which contains the elapsed time (sec) from the start of an event was included for plotting purposes. The last 5 columns contain the pointing angles from the SPAS position at the time shown in column 1 to a specular point seen at 40, 30, 20, 10 and 0 km. The number 9999.9 in one of these columns indicates that the SPAS cannot see a specular point at that altitude.

TABLE 1

EXAMPLE OF OUTPUT

DAY HH:MM:SS	MISSION ELAPSED TIME (SEC)	ELAPSED TIME	HEIGHT OF THE SPECULAR POINT 40 KM	30 KM	20 KM	10 KM	0 KM
121/23:42:11.00	302937.00	66	14.95	15.01	15.08	15.14	15.20
121/23:42:12.00	302938.00	67	14.90	14.97	15.03	15.09	15.15
121/23:42:13.00	302939.00	68	14.85	14.92	14.98	15.04	15.11
121/23:42:14.00	302940.00	69	14.81	14.87	14.93	14.99	15.06
121/23:42:15.00	302941.00	70	14.76	14.82	14.88	14.95	15.01
121/23:42:16.00	302942.00	71	14.71	14.77	14.84	14.90	14.96
121/23:42:17.00	302943.00	72	14.66	14.73	14.79	14.85	14.92
121/23:42:18.00	302944.00	73	14.76	14.68	14.74	14.80	14.87
121/23:42:19.00	302945.00	74	14.57	14.63	14.69	14.76	14.82
121/23:42:21.00	302947.00	76	14.48	14.54	124.60	14.67	14.73
121/23:42:22.00	302948.00	77	14.43	14.49	14.56	14.62	14.68
121/23:42:23.00	302949.00	78	14.38	14.44	14.51	14.57	14.64
121/23:42:24.00	302950.00	79	14.33	14.40	14.46	14.52	14.59
121/23:42:25.00	302951.00	80	14.28	14.35	14.41	14.48	14.54
121/23:42:26.00	302952.00	81	14.24	14.30	14.36	14.43	14.49
121/23:42:27.00	302953.00	82	14.19	14.25	14.32	14.38	14.45
121/23:42:28.00	302954.00	83	14.15	14.21	14.28	14.34	14.41
121/23:42:29.00	302955.00	84	14.10	14.17	14.23	14.30	14.36
121/23:42:30.00	302956.00	85	14.06	14.12	14.19	14.25	14.32
121/23:42:31.00	302957.00	86	14.01	14.07	14.14	14.21	14.27
121/23:42:32.00	302958.00	87	13.96	14.03	14.09	14.16	14.22
121/23:42:33.00	302959.00	88	13.92	13.98	14.05	14.11	14.18
121/23:42:34.00	302960.00	89	13.87	13.94	14.00	14.07	14.13